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Principal Investigator: Prof. Gregory W. Wornell

Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, MA   02139-4307

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13. ABSTRACT (Maximum 200 words)

A broad program of forward-looking research was pursued within the context of this Young Investigator grant. The emphasis of the research was on the development of high performance, very low complexity techniques for reliable communication over a broad range of realistic wireless and wired networks. A unifying theme in the approaches to these problems has been an integration of interrelated perspectives from communication theory, information theory, signal processing theory, and control theory, together with the infusion of new concepts and ideas from emerging theories of nonlinear dynamics, chaos, and fractal geometry.

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A broad program of forward-looking research was pursued within the context of this Young Investigator grant. The emphasis of the research was on the development of high performance, very low complexity techniques for reliable communication over a broad range of realistic wireless and wired networks. A unifying theme in the approaches to these problems has been an integration of interrelated perspectives from communication theory, information theory, signal processing theory, and control theory, together with the infusion of new concepts and ideas from emerging theories of nonlinear dynamics, chaos, and fractal geometry.

As one component of the research, we developed promising new and bandwidth-efficient classes of time, frequency, and space diversity strategies for single- and multi-user wireless communication in multipath fading environments. A particular focus was our pioneering investigation of techniques for efficient space-time coding, i.e., algorithms for exploiting multiple-element transmitter antenna arrays in wireless networks. The techniques we developed and analyzed offer dramatic improvements in network reliability with very little computational complexity, even when the network is subject to tight delay and bandwidth constraints. Design techniques for both low-complexity coded and uncoded systems were developed, along with fundamental performance limits. Among other important results, we established that there are significant benefits to designing such adaptive arrays to take advantage of even very limited channel state information. Specific space-time coding algorithms were developed for this scenario, and show a dramatic performance enhancement over the best codes for channels when no channel state information is available.

Also within this component of the research, we developed a host of near-far resistant receiver structures for use with both conventional and recently-introduced spread-signature CDMA systems. In this area, we have develeloped novel recursive linear equalization algorithms and techniques for equalization based on iterative interference cancellation. The iterative techniques correspond to a "turbo-style" receiver structures for wireless communication systems subject to multipath fading effects. In these receivers, equalization, demodulation and decoding are performed via an efficient, low-complexity batch-interative algorithm, which provides a monotonically improving progression of symbol estimates that can be terminated at as desired to meet fidelity or computation constraints. Our results showed that effectively optimum decoding performance can in principle be achieved using these approaches with dramatically less computational complexity than has traditionally been required. Moreover, preliminary experiments on Navy underwater acoustical communication data yielded promising results.

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Another component of the project explored the use of nonlinear dynamics and chaos in the design of innovative analog error-protection codes for communications applications. In the chaos context, we developed communication-theoretic evidence that the properties of chaotic dynamical systems make them useful for channel coding in a variety of practical communication applications. To illustrate this, a novel analog code based on tent map dynamics and having a fast decoding algorithm was developed for use on unknown, multiple, and time-varying signal-to-noise ratio (SNR) channels, which are useful models for many practical low-delay wireless links. This code was shown to be an attractive alternative to both digital codes and linear modulation in such scenarios. Several properties and interpretations of the codes were developed, along with some methods for their optimization.

Also within the context of nonlinear dynamics, we undertook a investigation of potential nontraditional applications of soliton theory to the development of modulation and demodulation techniques for wireless and other channels. This work revealed that soliton theory can also be used to create novel analog codes with some intriguing performance characteristics. While preliminary in nature, these results suggest that it may be possible to develop practical new codes out of such a framework.

Another component of the research investigated the use of fractal traffic models in the design and management of efficient, next-generation packet-switched communication networks. In this area, we developed novel multiscale methods for analyzing packet-switched data networks with bursty traffic exhibiting fractal behavior. Exploiting insights from this analysis, we then used similar methods to develop complementary new multiscale traffic management strategies for more efficiently routing and serving packets in such networks.

In a different dimension of the research, we developed novel techniques for efficiently exploiting the availability of feedback in communication networks due to duplex link structure. In particular, new ultra-low complexity coding algorithms were developed for reliable communication over unreliable channels that exploit the availability of such feedback. A unique feature of these methods is that they adapt familiar, computationally extremely efficient source coding algorithms for channel coding applications. These codes, which are based on an efficient iterative compressed-error cancellation framework, are capacity-achieving in the sense that the associated error probabilities decay exponentially with average blocklength at any rate below the channel capacity. Moreover, these schemes are maximally optimal in the sense that for a given channel, the error exponent associated with these schemes is the best possible exponent achievable by any scheme.

Generalizations of these algorithms were developed for particularly harsh channel models characteristic of DoD applications. In particular, the class of practical, low-complexity, variable-rate coding schemes was extended to channels with memory, both known and unknown. These codes also require only a fixed number of computations per input sample independent of blocklength. For unknown channels, new universal (blind) communication algorithms that integrate Lempel-Ziv type source coding as an integral part of their processing were developed. Remarkably, these algorithms achieve performance effectively equal to that possible if the channel characterstics were known a priori, yet without requiring the use of any training data.

Extensions to multiple-acccess wireless networks were also developed, as were variants that allow the feedback rate to be optimized as a function of the application of interest. These extensions also appear to be promising for a variety of wireless and related applications.

In the context of sensor networks specifically, we developed practical, new, low-complexity coding and estimation algorithms for wireless sensor networks. These algorithms appear to be attractive for a wide range of military applications. These involve the use of novel dynamic quantizer bias control techniques we have developed that were motivated by stochastic resonance phenomena observed in biological sensor systems prevalent in nature. A feature of these techniques is that they are extremely economical in their use of power at the sensor.

Finally, at the end of the grant we began to develop and evaluate a highly promising new class of highly robust and efficient information embedding techniques for hiding data in a variety of different types of signals, ranging from speech and video waveforms, to a variety of types of imagery and graphics. Important applications of this versatile technology arise in a variety of Navy contexts, ranging from covert communication (e.g., embedding digital messages in acoustic waveforms corresponding to underwater biologic signals for LPD ship-to-ship, ship-to-sub, or ship-to-shore communication), to anti-spoofing and data authentication (e.g., embedding information into a digitally tranmitted military map or chart that would enable the receiving user to determine whether it had been tampered with), to backward-compatible upgrading of legacy communication infrastructure (e.g., embedding digital enhancement information on top of the analog transmission format corresponding to a pre-existing wireless or wireline communication system). The specific techniques being developed for these applications involve the use of a natural "dither modulation" strategy for creating indexed familes of quantizers. Analysis has revealed that fundamental information theoretic limits on information embedding can be approached arbitrarily closely using these

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methods. Much work and many important issues remain to be explored on this topic.

The results for this reporting period are described in detail in the following theses, patent, and papers.

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